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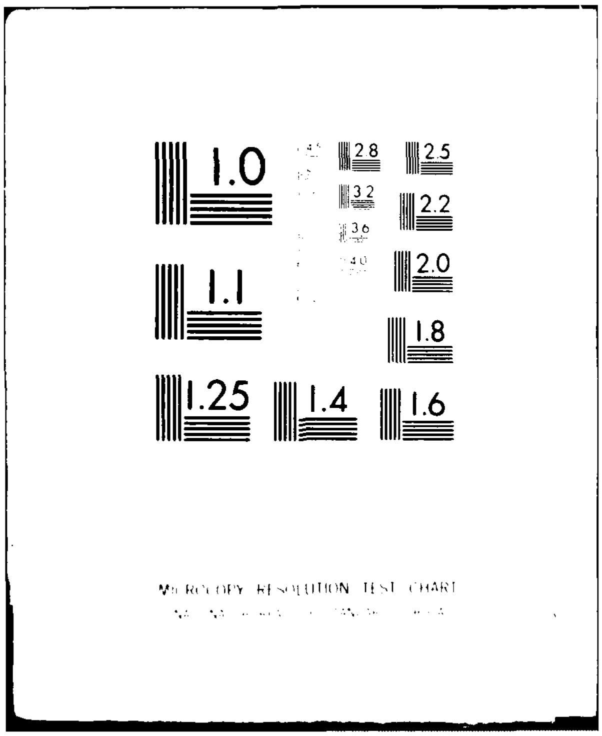
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A TECHNIQUE FOR CALIBRATING $\dot{V}$ PROBES

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Sandia National Laboratories
Albuquerque, NM 87185

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Final Report

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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The $\dot{V}$ probes designed by Maxwell Laboratories, Inc. (MLI) have been extensively used at the Air Force Weapons Laboratory to measure the voltage of fast capacitor banks. The straightforward calibration method of pulsing a high voltage across the voltage probe typically produces only millivolts of output signal. Based on a suggestion by MLI, a new method to calibrate the probes has been devised. This technique, which uses a capacitive discharge and measures the dV/dt directly, has the advantage of producing an output signal of nearly

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a volt. A circuit has been designed and constructed to provide an appropriate ringing discharge which can be used to calibrate $\dot{V}$ probes. In this report the theory of $\dot{V}$ probes and their calibration is discussed, and the construction and operation of the discharge circuit is presented. Finally, as an example of the calibration technique, details of how to calibrate a $\dot{V}$ probe are presented. A precision of 4 percent is readily attainable in the $\dot{V}$ probe calibration. Such accuracy should make possible routine 5 percent voltage measurement on pulsed power systems.

TABLE OF CONTENTS

I. INTRODUCTION

Measuring large transient voltages can be extremely difficult. Nevertheless, pulse power and plasma physics researchers frequently require an accurate measurement of such a fast, transient high voltage. Many techniques have been developed to measure pulsed high voltages. These include: capacitive dividers (Ref. 1), resistive dividers (Ref. 2), current transformer voltage probes (Ref. 3), and $\dot{V}$ probes (Ref. 4).

The $\dot{V}$ probes have a number of advantages over the other techniques. Unlike resistive dividers and current transformer voltage probes, a $\dot{V}$ probe depends upon capacitive pickup and requires no physical connection between the high and low voltage points. Moreover, while the long water resistors that are frequently associated with the resistive divider and current transformer voltage probe can have very slow frequency responses, the frequency response of a $\dot{V}$ probe is limited only by the electromagnetic wave travel time through the insulating medium. These times are short and permit a fast frequency response. A $\dot{V}$ probe does not require a large capacitance between the probe and ground. Rather, the capacitance to ground should be minimized. Therefore, a $\dot{V}$ probe is typically much smaller than a capacitive divider; moreover, a $\dot{V}$ probe does not require a large series resistance as a capacitive divider often does.

Figure 1 shows a simplified schematic of a $\dot{V}$ probe. The probe consists of a capacitor, C_p, and a termination resistor, R_t. The equation describing this circuit is:

$$R_t I + \frac{1}{C_p} \int I dt = V_o \sin wt \qquad (1)$$

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1. Burch, F. P., Phil. Mag., Vol. 13 Ser. 7, 760, 1932.

2. Thomas, R. J., "IEEE Transactions on Instrumentation and Measurement," IEEE, IM-19, 102, 1970.

3. McClenahan, C. R. and Henderson, R. P., Review of Scientific Instruments, Kirtland AFB, to be published.

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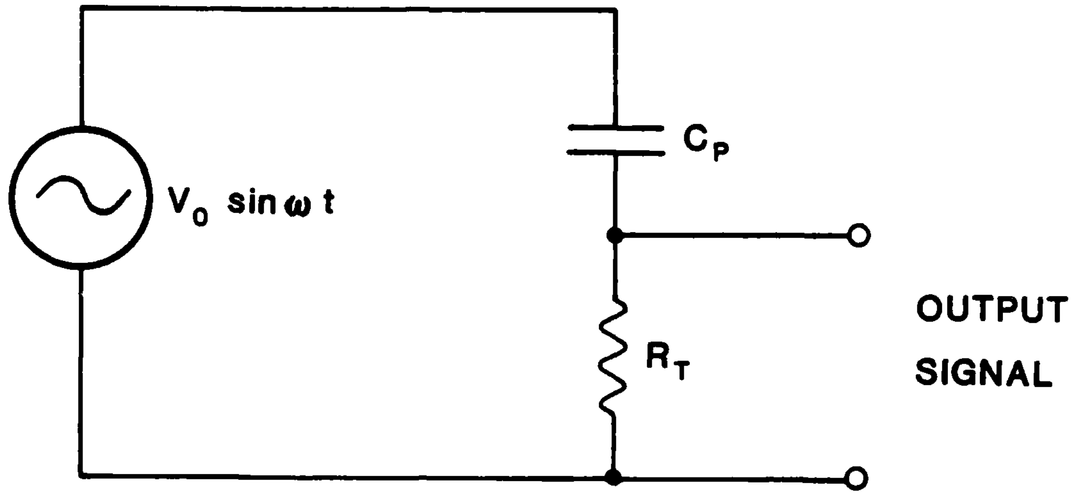

FIGURE 1. Schematic of a $\dot{V}$ probe

where $\int I dt$ is the charge on C_p, and $V_o \sin \omega t$ is the signal across the probe. Assuming that the charge on C_p is zero at $t = 0$, the solution to this equation gives:

$$I = \frac{V_o \omega C_p}{1 + \omega^2 R_t^2 C_p^2} \left[\cos \omega t + R_t C_p \, \omega \sin \omega t - e^{-t/R_t C_p} \right] \tag{2}$$

Now, assume that for any time of interest,

$$t >> R_t C_p \tag{3}$$

and

$$\frac{1}{\omega} >> R_t C_p \tag{4}$$

Then, the voltage across R_t can be approximated by:

$$V_t \approx R_t C_p \dot{V} \tag{5}$$

where

$$\dot{V} = V_o \omega \cos \omega t \tag{6}$$

Typically, $C_p \approx 1$ pF, and $R_t = 50$. Therefore, the conditions expressed in Equations 3 and 4 become

$$t >> 50 \text{ ps} \tag{7}$$

and

$$\omega << 2 \cdot 10^{10} \text{ s}^{-1} \tag{8}$$

These conditions are easy to meet. Another assumption that is implicit in the schematic of Figure 1 is that any impedance that is effectively in parallel with R_t must be much larger than R_t. Such an impedance is the reactance of the stray capacitance between the probe and ground. Therefore, the frequency response is limited by the stray capacitance. Conversely, the maximum tolerable stray capacitance is determined by the desired frequency response. For example, if 100 MHz response is desired, then the capacitance between the probe and ground must be:

$$C_g << \frac{1}{\omega R_t} = 32 \text{ pF} \tag{9}$$

Some care must be taken to ensure that this condition is met, and each $\dot{V}$ probe design must be evaluated in light of this condition.

The voltage is determined by integrating the $\dot{V}$ probe output. Normally, the output signal is passively integrated by an RC network at the oscilloscope input in the screen room. Any spurious noise signals are also integrated, and they generally become insignificant. This is a major advantage that $\dot{V}$ probes have over standard capacitive dividers.

II. TECHNIQUE

The problem then becomes one of accurately determining the calibration factors or sensitivity of a given $\dot{V}$ probe in a particular environment. In particular, the capacitance, C_p, in Equation 5 must be accurately determined.

The standard way to determine the sensitivity of a voltage probe is to pulse a high voltage across the probe and measure the integrated output. If a 1 kV square pulse is delivered to the probe, and a 10 μs integrator is used, the measured signal is only 5 mV. Clearly, this technique is subject to larger uncertainties introduced by small signal-to-noise ratios.

It was suggested that a capacitor could be discharged into the transmission line where the $\dot{V}$ probe was located, and the dV/dt be measured directly.* In this way, the measured signals would be very much larger (~ 1 V). Figure 2 shows schematically how this is done. Initially, C_c is charged to

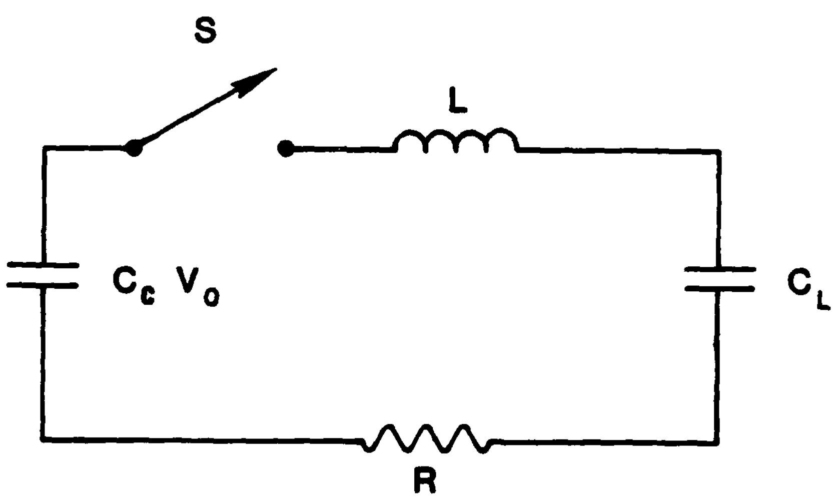

FIGURE 2. Simplified schematic of circuit to apply a time varying voltage to a $\dot{V}$ probe. $\dot{V}$ probe is in parallel with C_L.

*Reinovsky, R., and Shannon, J., private communications.

a voltage V_o and there is no current flowing. If C_c is substantially larger than the transmission line capacitance, C_L, the voltage on C_L will ring up to twice V_o. The current in the circuit will be given by:

$$I = \frac{V_o}{\omega L} e^{-\alpha t} \sin \omega t \tag{10}$$

where $\alpha = R/2L$ is the damping constant and $\omega = \left(\left(1/C_c + 1/C_L\right)/L - \alpha^2\right)^{1/2}$ is the frequency, and the voltage across the transmission line (and the $\dot{V}$ probe) is characterized by:

$$\dot{V} = \frac{I}{C_L} \tag{11}$$

Therefore, to accurately determine the $\dot{V}$ across the probe, only the current flowing to the transmission line and the line capacitance need to be accurately known.

The transmission line capacitance can be accurately measured in at least two ways. First, a low frequency capacitance bridge can be used to directly measure the capacitance. The second technique was reported by Riney, Schmid, and Hackerman in which C_L is charged through a known resistance from a known rectangular voltage pulse (Ref. 5). The latter technique is extremely insensitive to any inductance in the system, and it allows one to use relatively high frequencies to measure C_L. Both methods were successfully used to determine C_L.

5. Riney, J. S., Schmid, G. M., and Hackerman, N., Rev. Sci, Instrum. 32, p. 588, 1961.

III. APPARATUS

The actual circuit that was built to calibrate $\dot{V}$ probes is housed in a 5 in x 6 in x 7 in aluminum chasis box with the power transformer mounted on the outside. The unit is entirely self-contained and portable. One hundred twenty volt AC power is supplied through a standard power cord. Other input and outputs are via coaxial connectors. Figure 3 shows a schematic of the circuit which pulse charges C_L as shown in Figure 2. The circuit can be divided into five functional groups: (1) high voltage supply, (2) energy storage capacitor, (3) switch, (4) current monitor, and (5) inductor.

The high voltage supply is a standard full wave bridge rectifier. A Traid type R11A power transformer supplies 700 VAC to the bridge. Filtering is accomplished by the 1 MΩ charging resistor and the 0.25 μF primary discharge capacitor. This capacitor is charged to about 900 VDC. The AC ripple on the capacitor is about 10 V.

The switch is an EG&G Krytron. It is triggered by applying the output of a TR-149 transformer to the trigger grid. A positive pulse of about 30 V applied to the input of the trigger transformer is sufficient to fire the Krytron. The 22 MΩ resistor connected between the anode and the keep alive grid and the 22 MΩ resistor from the output to ground provide current for the necessary preionization. The output of the switch is the cathode of the Krytron.

The obvious way to measure the current is to insert a resistor into the circuit and measure the voltage developed across the resistor. This resistor can be selected so that it will have a minimal effect on the circuit behavior. For example, if the effective capacitance is 10 nF and the inductance is 1 μH, then the frequency is $10^7\ s^{-1}$. Therefore, if the damping constant were $10^6\ s^{-1}$, it would not seriously alter the circuit behavior; i.e., a resistance of 2Ω would not adversely effect the circuit. Nevertheless, a series resistor does have a serious drawback. To measure the voltage across the resistor, one of two things must be done: either the resistor is on the ground side of the transmission plate and all other ground paths must be broken, or the resistor is on the high voltage side and the signal detector (e.g., oscilloscope) must be floating. Both of these alternatives can be extremely difficult to accomplish.

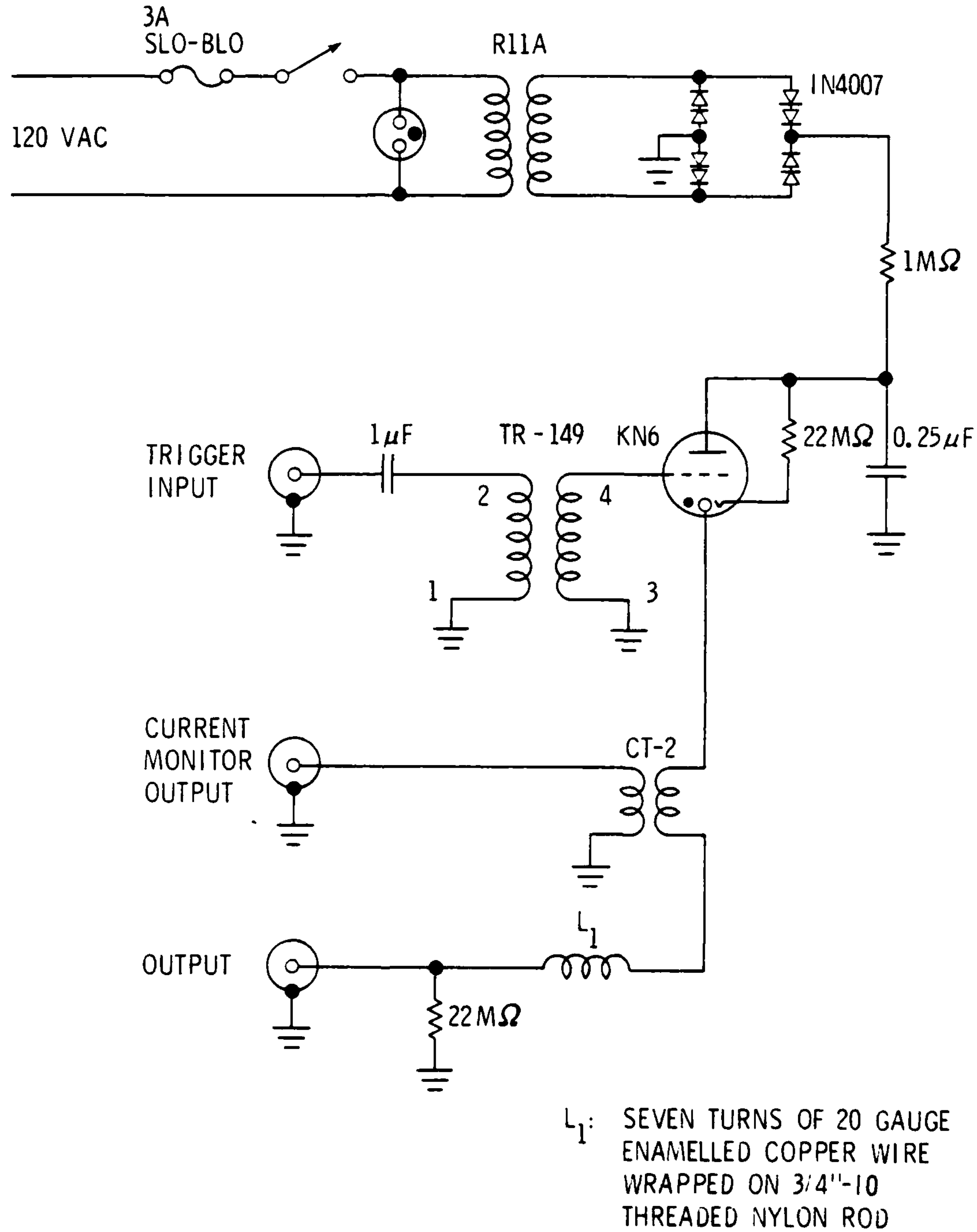

FIGURE 3. Krytron switch $\dot{V}$ probe calibration capacitive discharge circuit schematic.

Rather than attempt either of these, it was decided to use a different technique. A current transformer located on the high voltage side of the discharge will provide the necessary isolation to permit the oscilloscope to be operated normally. Moreover, alternate paths between the ground side of the transmission line and the system ground need not be broken. Also, a current transformer has a negligible effect on the discharge circuit behavior. Clearly, a current transformer eliminates the problems associated with a current-viewing resistor (CVR) and is the choice for measuring the discharge current. The current transformer used to measure the Krytron cathode current is a Tektronix CT-2. Its frequency response is flat between 30 kHz and 50 MHz, and its 3 percent accuracy is comparable to what can be read from an oscilloscope trace (Ref. 6). Moreover, its intrinsic 1 kV insulation allows it to be located on the high voltage side of the discharge. Nevertheless, to protect the transformer from the twice V_0 ring up voltage on the transmission line capacitance, an inductor, L_1, was placed between the current transformer and the circuit output. The inductor L_1 is the dominant inductance in the circuit.

Figure 4 shows the output of the current transformer when the calibration circuit was fired into a 10.45 nF capacitor. The half period leads to a frequency (ω) of $8.9 \cdot 10^6$ s^{-1} and an inductance of 1.2μH. The peak current was 74A. There was a 6 percent transmission line loss between the current transformer and the oscilloscope, because the signal was transmitted through about 100 ft of cable. With this correction Equation 10 can be used to deduce that the initial voltage of C_c was 840 V. A VOM used to measure the voltage gave 870 V.

6. CT-2 Instruction Manual, Tektronix, Inc., Beaverton, OR, 1963

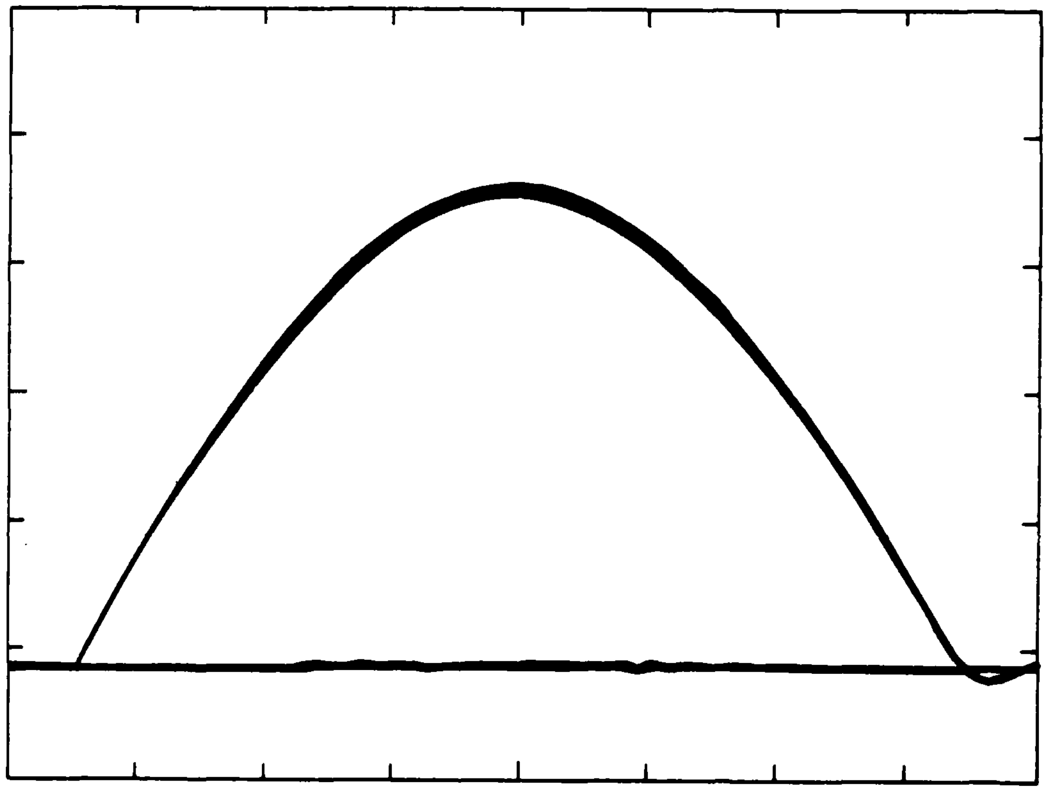

FIGURE 4. Current resulting from discharge of circuit in Figure 3 into 10.45 nF reference capacitor. Approximately 20 A/div and 50 ns/div.

IV. PROCEDURES

The circuit as described was used to measure the sensitivity of a $\dot{V}$ probe installed in the transmission line of a 500 kJ fast capacitor bank in use at the Air Force Weapons Laboratory. Figure 5 is a drawing of the $\dot{V}$ probe, which was designed and manufactured by Maxwell Laboratories Inc. These probes have been in use since 1975. The nominal capacitance of the probe is 1 pF.

Figure 6 shows the discharge current of the Krytron circuit into the transmission plate and the $\dot{V}$ probe output. Obviously, noise is not a problem. These oscillograms were obtained using Tektronix type R7603 oscilloscopes. The sensitivity of the vertical deflection systems of the scopes were determined by using a 1.02 V calibrated standard voltage cell, and the sweep speeds were determined by using a General Radio model 1330-A radio frequency oscillator and a Hewlett-Packard model 5245L frequency counter. The vertical deflection sensitivity and sweep speed are known to within 2 percent. All of the terminators and attenuators used were measured with a General Radio model 1608A impedance bridge. The current transformer was calibrated using a Hewlett-Packard model 8012A pulse generator. The precision of this measurement (3 percent) was the poorest of any of the calibration measurements.

The capacitance of the transmission line, C_L, was measured by two techniques. First, the impedance bridge gave $C_L = 4.90 \pm 0.05$ nF at 1 kHz. Second, charging the transmission line through a resistor with a 4 μs square pulse gave $C_L = 4.90 \pm 0.12$ nF. The resistor used in the latter was measured by the same impedance bridge to be 21.26 kΩ and, independently by the Precision Measurement Equipment Laboratory, Kirtland AFB, to be 21.25 ± 0.02 kΩ.

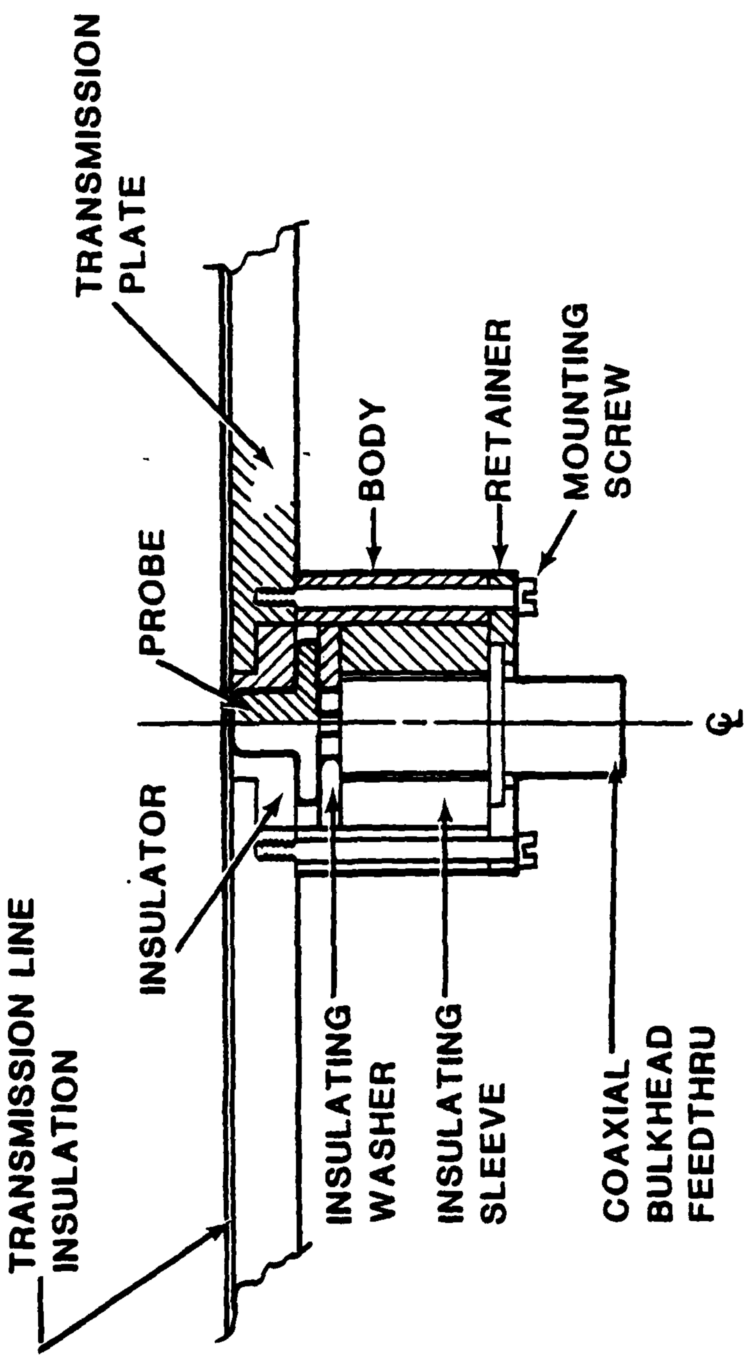

FIGURE 5. Cross-sectional drawing of the $\dot{V}$ probe

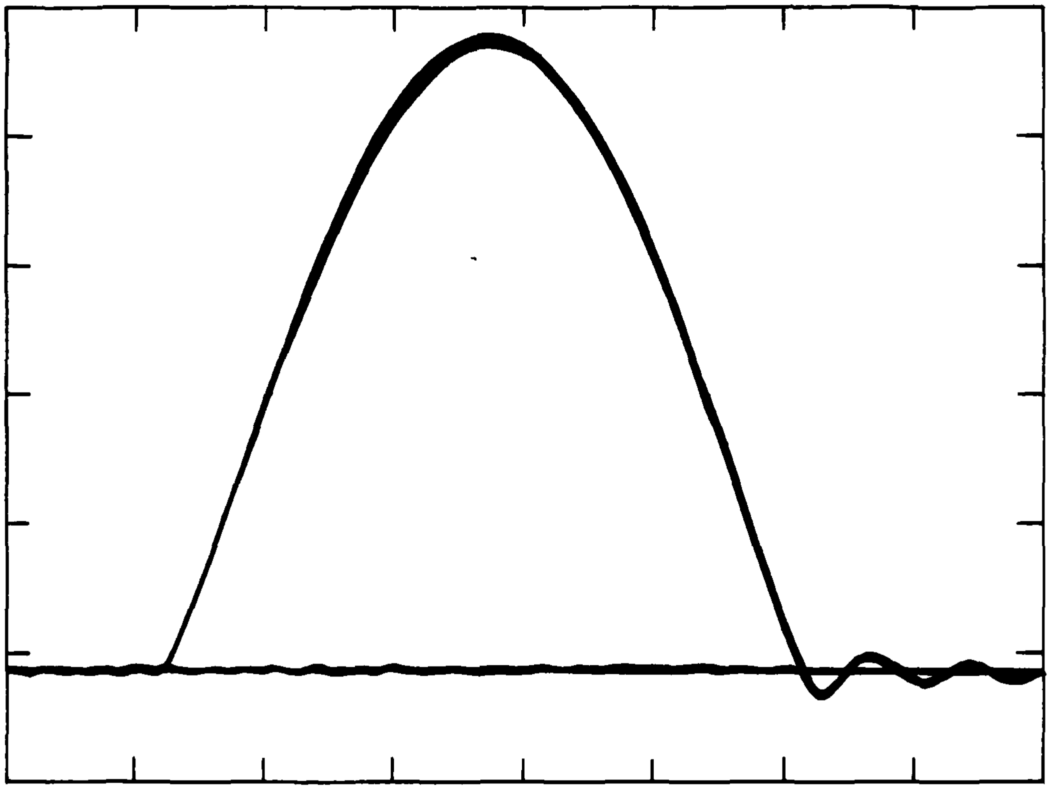

FIGURE 6a. Discharge current into the transmission line. Approximately 10 A/div and 50 ns/div.

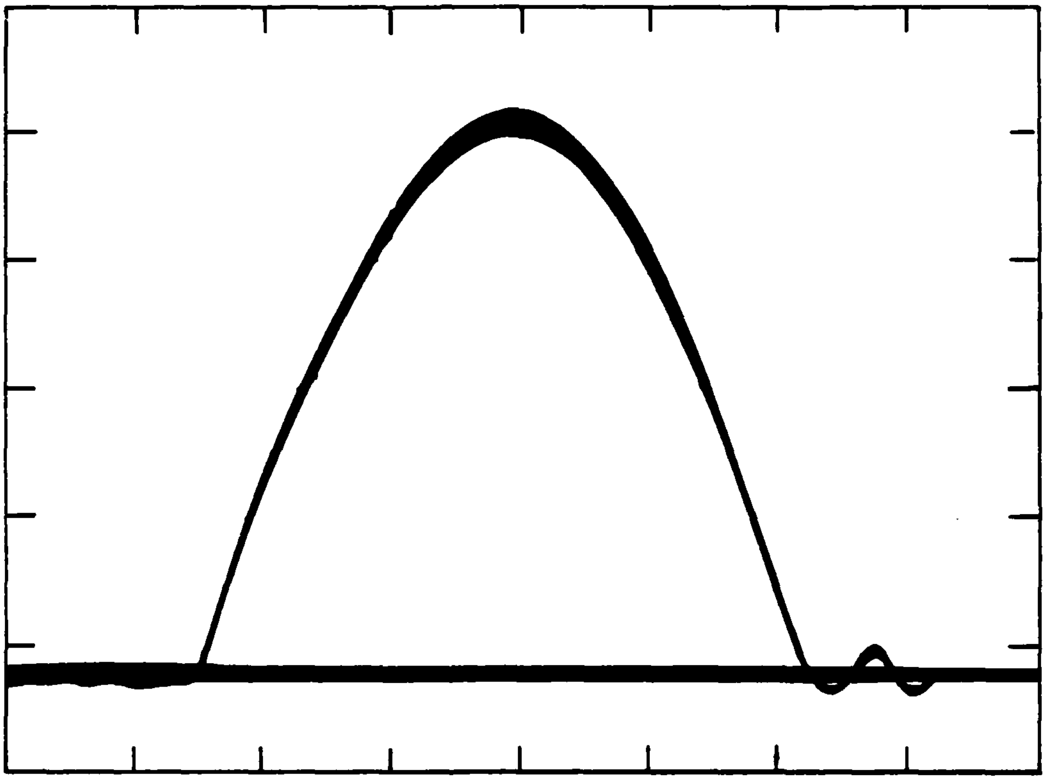

FIGURE 5h. $\dot{V}$ probe output. Approximately 0.1 V/div and 50 ns/div.

The peak discharge current (Fig. 6a) was 47.3 $\pm$ 1.5 A. Therefore, the peak $\dot{V}$ was 9.7 $\pm$ .3 kV/μs. The peak $\dot{V}$ probe output voltage (Fig. 6b) was V_p = 0.45 $\pm$ 0.01 V. Using the known resistance of the terminator (49.75 $\pm$ 0.05Ω), the capacitance of the $\dot{V}$ probe is:

$$C_p = \frac{V_p}{\dot{V}R_t} = 0.93 \pm 0.04 \text{ pF} \tag{12}$$

A 6 percent transmission line loss was measured for the signal. However, since both the current transformer and $\dot{V}$ probe output signals went through the same length of RG-214/U cable, and the frequency of both signals was the same, the losses cancel. Nevertheless, when the $\dot{V}$ probe is used to measure a voltage waveform, signal cable losses must be considered.

V. SUMMARY

The $\dot{V}$ probes can be very useful devices for measuring a pulsed high voltage. A new calibration technique for these probes has been developed. Discharging a special triggered capacitor calibration circuit into the capacitance that exists between the high and low voltage points provides a means of calibrating the $\dot{V}$ probe, and with reasonable care, a 4 percent determination of the probe sensitivity is readily attainable. Therefore, 5 to 6 percent measurements of high voltage pulses from machines such as Hermes II are routinely possible with $\dot{V}$ probes.

In use, the output signal of a $\dot{V}$ probe is typically integrated by a passive integrator, which leads to a substantial reduction in measured signal. This technique, however, measured the $\dot{V}$ signal directly. Consequently, the measured signals are relatively large. Moreover, the output signals are quite free of noise. This circuit is simple and reliable, and used as described, it provides a convenient and accurate way to calibrate $\dot{V}$ probes.

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2. Thomas, R. J., "IEEE Transactions on Instrumentation and Measurement," IEEE, IM-19, p. 102, 1970.
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5. Riney, J. S., Schmid, G. M., and Hackerman, N., Rev. Sci, Instrum. 32, p. 588, 1961.
6. CT-2 Instruction Manual, Tektronix, Inc., Beaverton, OR, 1963.

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